NEAR-INFRARED PHOTOMETRIC MONITORING OF A PRE-MAIN-SEQUENCE OBJECT KH 15D

Nobuhiko Kusakabe[1], Motohide Tamura[1,2], Yasushi Nakajima[2]

Ryo Kandori[2], Akika Ishihara[2], Tetsuya Nagata[3]

Takahiro Nagayama[3], Shogo Nishiyama[4], Daisuke Baba[4]

Shuji Sato[4], Koji Sugitani[5], Edwin L. Turner[6]

Lyu Abe[2], Hiroshi Kimura[7], Tetsuo Yamamoto[7]

ABSTRACT

An extensive photometric monitoring of KH 15D, an enigmatic variable in the young star cluster NGC 2264, has been conducted. Simultaneous and accurate near-infrared (*JHKs*-bands) photometry is presented between 2003 December and 2005 March covering most of the variable phase. The infrared variability is characterized by large-amplitude and long-lasting eclipse, as observed at optical. The period of variability is 48.3 ± 0.2 days, the maximum photometric amplitude of variability is $\sim$4.2 mag, and the eclipse duration is $\sim$0.5 in phase units. These are consistent with the most recent period, amplitude, and duration at optical. The blueing of the *J*-*H* color ($\sim$0.16 mag) during the eclipse, which has been suggested before, is unambiguously confirmed; a similar blueing at *H*-*Ks* is less clear but is probably present at a similar level. The overall shape of the *JHKs* light curves is very similar to the optical one, including a fair time-symmetry and a less stable flux during the eclipse with a slight hump near the zero phase. Most of these variability features of KH 15D observed at near-infrared wavelengths can be explained with the recent model employing an eclipse by the inclined, precessing disk and an outer scattering region around a pre-main-sequence binary.

Subject headings: circumstellar matter - stars: individual (KH 15D) - stars: pre-main-sequence - planetary systems: protoplanetary disks

[1]Department of Astronomical Science, Graduate University for Advanced Studies (Sokendai), Osawa, Mitaka, Tokyo 181-8588, Japan; kusakabe@optik.mtk.nao.ac.jp.

[2]National Astronomical Observatory of Japan, Osawa, Mitaka, Tokyo 181-8588, Japan; hide@subaru.naoj.org.

[3]Department of Astronomy, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan.

[4]Department of Astrophysics, Faculty of Sciences, Nagoya University, Chikusa-ku, Nagoya 464-8602, Japan.

[5]Graduate School of Natural Sciences, Nagoya City University, Mizuho, Nagoya 467-8501, Japan.

[6]Princeton University Observatory, Peyton Hall, Princeton, NJ 08544.

[7]Institute of Low Temperature Science, Hokkaido University, Sapporo 060-0819, Japan.

1. INTRODUCTION

KH 15D (V582 Mon; $6^{\rm h}41^{\rm m}10\overset{\rm s}{.}18$, $9°28'35''\!.5$, J2000) is a K6-7 pre-main-sequence star (Agol et al. 2004; Hamilton et al. 2001) in NGC 2264 (d = 760 pc), which shows a unique variability. This is the star #15 in the D field of Kearns & Herbst (1998). See Maffei, Ciprini, and Tosti (2005) for other identifications of this object. The optical variability is characterized by a large eclipse amplitude (maximum ∼4.0 mag in I-band between 1999 and 2004; Barsunova, Grinin, & Sergeev 2005; Johnson et al. 2005; Hamilton et al. 2005) and a long eclipse duration, about half of its period (currently ∼24 days out of ∼48 days; Winn et al. 2004; Johnson et al. 2005). The eclipse duration has been increasing with time, by 1-2 days per year. A great deal of information about this system has been obtained from archival studies (Winn et al. 2003; Johnson & Winn 2004; Johnson et al. 2005). The eclipses were formerly much shallower and the system was brighter overall. During the eclipse a slight blueing of the star's color indices (Herbst et al. 2002; Hamilton et al. 2005), little or no change in spectral type (Hamilton et al. 2001), relatively large flux fluctuations (Herbst et al. 2002; Barsunova et al. 2005), and a dramatic increase in linear optical polarization (Agol et al. 2004) are observed. The latter measurements suggest that a substantial fraction or all of the light in eclipse is scattered light.

At near-infrared wavelengths, no color change or marginal blueing during the eclipse is reported (Knacke, Fajardo-Acosta, & Tokunaga 2004). Molecular hydrogen emission at 2.12 μm presumably associated with the mass outflow from this source has been detected (Deming et al. 2004; Tokunaga et al. 2004), which can be circumstantial evidence for a disk around the central star(s). Recent spectroscopic monitoring has revealed that the system is in fact a single-lined spectroscopic binary with the same period of the eclipse (Johnson et al. 2004). These remarkable properties are now explained by the theory that a binary star is gradually occulted by an inclined and precessing circumbinary disk (Winn et al. 2004) or narrow ring (Chiang & Murray-Clay 2004).

In spite of the recent intensive interests in this unusual object, a very limited amount of infrared monitoring is reported, which must be indispensable to understanding the occulting material, the dust extinction properties, and the contribution of dust thermal emission, if any. In order to better understand the enigmatic variability of this source, we have started a long-term monitoring of KH 15D at $JHKs$ simultaneously from 2003 December. In this *Letter*, we present the magnitudes and colors for the first 16 months (54 independent data points), which covers most of its variable phase (ϕ) and serves as the most extensive near-infrared monitoring data of KH 15D to date, and interpret the data based on the disk-eclipse model for this system.

2. OBSERVATIONS

We carried out imaging observations of the field centered around KH 15D in the near-infrared bands J (λ_c = 1.25 μm), H (1.63 μm), and Ks (2.14 μm) simultaneously. The observations were made during 2003 December and 2005 March with the near-infrared camera SIRIUS on the IRSF

1.4-m telescope at Sutherland, South Africa. The camera is equipped with three 1024×1024-pixel HgCdTe (HAWAII) arrays. Two dichroic mirrors enable simultaneous observations in the three bands. Details of the camera are described in Nagashima et al. (1999) and Nagayama et al. (2003). The image scale of the array is $0\farcs45$ pixel^{-1}, giving a field of view of $7\farcm7 \times 7\farcm7$.

We measured 54 independent data points during this period. We obtained 90 dithered frames with typical exposure time of 10 seconds, resulting in the total integration time of 900 seconds for each data point. Typical seeing was $1\farcs4$ (FWHM), ranging from $1''$ to $2''$, in the *Ks* band. The standard star No. 9116 in the faint infrared standard star catalog of Persson et al. (1998) was observed for the photometric calibrations.

We used NOAO IRAF software package to reduce the data. We applied the standard procedures of near-infrared array image reduction, including dark current subtraction, sky subtraction and flat fielding. See Nakajima et al. (2005) for the details of the SIRIUS image reductions. Identification and photometry of point sources were performed by using the DAOFIND and PHOT tasks in IRAF, respectively. The aperture radius for the photometry was 3 pixels ($1\farcs35$).

3. RESULTS

Fig. 1 shows a *JHKs* composite color image of the observed region including KH 15D. The field also includes the famous infrared YSO, NGC 2264 IRS1 (Allen 1972) and the top of the Cone Nebula. Note that KH 15D, situated at $\sim 50''$ to the south of IRS1, is also somewhat affected by the nebula associated with IRS1. In order to accurately measure the photometric variability of KH 15D, we employed relative photometry within the field. First we checked the variability of each source in the field compared with the median of all the sources among various nights. Then only the sources whose rms errors of magnitudes are less than 3σ are selected. This process was repeated three times. Finally six sources in the field whose non-variability were confirmed with the above processes were selected (Fig. 1).

Fig. 2 shows the *JHKs* light curves of KH 15D after calibrating with the photometric standard star (The data are in Table 1; electronic form only). The periodicity seen at optical wavelengths is clear even in this figure. We determined the periods of the *JHKs* light curves to be the same, 48.3 ± 0.2 days. This is also identical to the most recent optical period.

Phased light curves using the optical period of 48.36 days (Herbst et al. 2002) are shown in Fig. 3. The overall shape of each light curve is very similar to the optical one:

(1) The light curves at *JHKs* show a fairly good symmetry with time, though the detailed shape has some asymmetry. For example, the slopes of the first decrease or increase (ϕ = -0.25 – -0.15 and 0.15 – 0.25) are slightly different with each other. Similar changes in slopes are observed at optical (Herbst et al. 2002; Barsunova et al. 2004). Note that the beginning and ending of the eclipse is not as abrupt as seen in the 2001-2002 optical data (Herbst et al. 2002).

(2) The maximum photometric variability amplitudes are nearly identical at *JHKs*, $\sim$4.2 mag. These values are consistent with the optical amplitude of $\sim$4.0 mag (in *I*-band between 1999 and 2004, after correcting for the monotonous flux decrease trend; Barsunova et al. 2005; Johnson et al. 2005). The average amplitudes at *JHKs* are $\sim$3.6 mag. Note that the large fluctuations during the eclipse make an accurate comparison of the values between infrared and optical difficult.

(3) The flux during the eclipse is less stable, and there is a clear flux hump near $\phi = 0$. The hump at *JHKs* is at a level of 0.5 mag and continues about $\sim$4 days. This hump is also observed at optical (Herbst et al. 2002; Barsunova et al. 2005). Two minima occur at $\phi \sim \pm 0.1$; the minimum at $\phi = +0.1$ appears deepest.

(4) The duration of the eclipse in 2003-2005 (0.52 in phase units at FWHM) is larger by 30% than the optical duration in 2001-2002 (0.4; Herbst et al. 2002), and is rather consistent with the most recent (2003-2004) optical data (0.5; Hamilton et al. 2005). There is no difference of the duration phase among *JHKs*.

Fig. 4 shows the phased color curves of KH 15D (*J-H*, *H-Ks*). Outside of the eclipse the *J-H* and *H-Ks* colors of KH 15D are constant, (0.68 $\pm$ 0.01) and (0.28 $\pm$ 0.02) in magnitudes, respectively, which match those of the K7-type T Tauri stars (e.g., V410 Tau) with a slight reddening ($A_V \sim 1$ mag). Knacke et al. (2004) derived the same spectral type from the average non-eclipse colors of *J-H* = 0.67 and *H-K* = 0.18. Note that the IRSF/SIRIUS color system is almost identical to the MKO system. The derived spectral type is consistent with the optical one (Hamilton et al. 2001; Agol et al. 2004).

Most striking is the clear change of infrared colors during the eclipse. As seen in Fig. 4, the blueing of *J-H* color ($\Delta m = 0.16$ mag) during the transit is unambiguously confirmed in our observations. Such blueing has been first reported at optical (Herbst et al. 2002; see Hamilton et al. 2005 for the most recent optical data) but only marginally suggested at near-infrared by Knacke et al. (2004). The blueing of *H-Ks* color is less clear but seems to be at a similar level ($\Delta m \sim 0.1$ mag). The average *J-H* and *H-Ks* colors during the eclipse are (0.52 $\pm$ 0.05) and (0.18 $\pm$ 0.12) in magnitudes, respectively.

No positional shift of KH 15D is observed between the on- and off-eclipse periods, which suggests that a contamination by an interloper is unlikely the cause of the blueing. In order to crosscheck this, we have considered possible blue sources. Such a source must have a color of *J-H* < 0.52 (= 0.68 - 0.16) mag to explain the observed blueing. Since the visual extinction at the location of KH15D is larger than $A_V = 10$ mag or *J-H* = 1.1 mag (Simon & Dahm 2005), the intrinsic color must be *J-H* < -0.58 mag. No foreground or background star or background galaxy with such a blue intrinsic color is expected to interlope our $1''.35$ aperture radius.

4. DISCUSSION

The most plausible model of these enigmatic variable features of KH 15D is the theory that a binary star in a mutual orbit with high eccentricity is gradually occulted by an inclined and precessing circumbinary disk (Winn et al. 2004) or narrow ring (Chiang & Murray-Clay 2004). The existence of such a companion has been recently confirmed by radial velocity measurements (Johnson et al. 2004); the orbital parameters agree well with the prediction by Winn et al. (2004). The long-term change of the variability characteristics revealed by archival studies (Winn et al. 2003; Johnson & Winn 2004; Johnson et al. 2005) is also explained with the same idea. Today, only one component of the binary is visible (we refer to this component as Star A), with the other component (Star B) being entirely hidden behind the disk. By employing this theory, we consider the near-infrared and optical features that are explainable as follows:

(a) Both the large variability amplitude and the long-lasting periodic eclipse that are almost independent of the observed wavelengths (*VRIJHKs*) are well explained with a gradual occultation by a knife edge screen. In this case, the screen is either a circumbinary disk or ring, and the disk dust size responsible for the screening must be much larger than the observed wavelengths ($\gg 2$ μm). The rough time-symmetry of the light curve is also explained with this theory. The detailed asymmetric features during the eclipse are probably due to the fine structures and kinematics of the disk or ring, which needs future detailed modeling.

(b) The near-infrared color blueing as well as the optical one indicates that the eclipse is not due to the disk dust absorption which causes "reddening". As described below, the blueing can also be explained by the eclisping disk model with an outer scattering region. This is consistent with the increase of optical polarization during the eclipse which suggests that a large fraction of the light in eclipse is scattered light (Agol et al. 2004).

The polarization data suggest that the scattering region is not completely obscured by the occulting material. The dust in this scattering region, which is distinct from the screening dust mentioned above, must be responsible for both the color blueing and the polarization. In order to explain these, we have calculated light scattering by dust grains in the non-occulted, scattering region. We have assumed the scattering region to be a semi-sphere over the eclipsing disk, the dust spatial distribution to follow $r^{-1.5}$ (corresponding to free-falling dust), and the dust material to be silicate (Laor & Draine 1993), and the dust size distribution to follow $a^{-3.5}$ with a_{min} = 0.5 nm and a_{max} = 5 μm. The radius of the semi-sphere is 2.6 AU with its equatorial plane inclined by 20° to the line-of-sight (Winn et al. 2004). The resultant color changes and optical polarization of the integrated scattered light are $\Delta m = 0.16$ mag for *J-H* and 0.18 mag for *H-Ks*, and p(optical)=2%, respectively. Although detailed modeling of the geometry and dust grains is beyond the scope of this paper, this simple model quantitatively well reproduces both our observed color changes and the polarizations by Agol et al. (2004).

Since there is no sign of *H-Ks* color excesses, the possible thermal emission from the disk suggested from the model or the H_2 outflows appears insignificant at near-infrared.

(c) The hump near $\phi = 0$ is probably due to some flux contribution of the unseen star (Star B) of the binary in the Winn's model because the Star B is nearest to the occulting edge at the middle of the eclipse. The amplitude is ~0.5 mag at *JHKs*, almost identical to the amplitude at *I* (in 2002-2003, Johnson et al. 2005). The optical color tends to be slightly bluer near this hump compared with other eclipsing color (Hamilton et al. 2005), which might support the interpretation that some additional light (from Star B) increases at this time. Since such a change of our near-infrared color near this hump is not conclusive, a more accurate and intensive monitoring during this phase is necessary.

5. CONCLUSIONS

We have conducted *JHKs* monitoring of KH 15D in NGC 2264 between 2003 December and 2005 March. The main conclusions of this paper are as follows:

(1) The *JHKs* light curves are very similar to the optical light curve, which show a fairly good time-symmetry and a slight flux hump near the zero phase.

(2) The *JHKs* period is the same as the optical period, 48.3 days.

(3) The maximum *JHKs* variability amplitude at near-infrared is ~4.2 mag.

(4) The eclipse durations are identical among *JHKs* (0.52 in phase units from 2003 to 2005).

(5) The blueing of *J-H* color ($\Delta m = 0.16$ mag) during the transit is unambiguously confirmed, while the blueing of *H-Ks* color appears at a similar level.

(6) These near-infrared variability features can be explained with the model employing an eclipse by the inclined and precessing disk or ring around a pre-main-sequence binary. The dust in the disk causing the eclipse is very large in size (a $\gg 2$ μm), therefore the eclipse is independent of wavelengths, while the dust responsible for the scattered flux during the eclipse is outside of the disk and smaller in size ($a_{max} \sim 5$ μm), causing the color-blueing and the polarization only during this phase.

We are grateful to Josh Winn and Chie Nagashima for helpful comments. We thank T. Tanabe, R. Kadowaki, and Y. Haba for their help in observations. We acknowledge M. Fukagawa, T. Naoi, and N. Kaneyasu for helpful discussions and assistance. We also thank the referee John Stauffer for his useful suggestions. MT, TN, HK, TY and SS are supported by Grants-in-Aid from the Ministry of Education, Culture, Sports, Science, and Technology.

REFERENCES

Agol, E., Barth, A. J., Wolf, S., & Charbonneau, D. 2004, ApJ, 600, 781

Allen, D. 1972, ApJ, 172, L55

Barsunova, O. Y., Grinin, V. P., & Sergeev, S. G. 2005, Astrophysics, 48, 1

Chiang, E. I., & Murray-Clay, R. A. 2004, AJ, 607, 913

Deming, D., Charbonneau, D., & Harrington, J. 2004, ApJ, 601, L87

Hamilton, C. M., Herbst, W., Shih, C., & Ferro, A. J. 2001, AJ, 554, L201

Hamilton, C. M., et al. preprint (astro-ph 0507578)

Herbst, W., et al. 2002, PASP, 114, 1167

Johnson, J. A., & Winn, J. N. 2004, AJ, 127, 2344

Johnson, J. A., Marcy, G. W., Hamilton, C. M., Herbst, W., & Johns-Krull, C. M. 2004, AJ, 128, 1265

Johnson, J. A., et al. 2005, AJ, 129, 1978

Kearns, K. E., & Herbst, W. 1998, AJ, 116, 261

Knacke, R., Fajardo-Acosta, S., & Tokunaga, A. T. 2004, AJ, 128, 2977

Laor, A., & Draine, B. T. 1993, ApJ, 402, 441

Maffei, P., Ciprini, S., & Tosti, G. 2005, MNRAS, 357, 1059

Nagashima, C., et al. 1999, in Star Formation 1999, ed. T. Nakamoto (Nobeyama: Nobeyama Radio Obs.), 397

Nagayama, T., et al. 2003, Proc. SPIE, 4841, 459

Nakajima, Y., et al. 2005, AJ, 129, 776

Persson, S. E., Murphy, D. C., Krzeminski, W., Roth, M., & Rieke, M. J. 1998, AJ, 116, 2475

Simon, T., & Dahm, S. E. 2005, ApJ, 618, 795

Tokunaga, A. T. et al. 2004, ApJ, 601, L91

Winn, J. N., Garnavich, P. M., Stanek, K. Z., & Sasselov, D. D. 2003, ApJ, 2003, 593, L121

Winn, J. N., Holman, M. J., Johnson, J. A., Stanek, K. Z., & Garnavich, P. M. 2004, ApJ, 603, L45

[!htb]

This preprint was prepared with the AAS LaTeX macros v5.2.

Table 1. Near infrared photometry of KH 15D.

JD(day)	J	J err	J-H	J-H err	H-Ks	H-Ks err
2452989.42	16.88	0.03	0.51	0.04	0.25	0.02
2453002.38	13.42	0.02	0.65	0.03	0.27	0.01
2453066.41	16.51	0.03	0.54	0.04	0.16	0.04
2453075.28	17.16	0.02	0.47	0.03	0.13	0.02
2453078.30	17.07	0.02	0.52	0.03	0.13	0.03
2453291.59	13.42	0.02	0.68	0.02	0.27	0.02
2453292.59	13.41	0.01	0.67	0.01	0.27	0.02
2453293.59	13.41	0.01	0.67	0.01	0.30	0.01
2453302.61	13.45	0.00	0.69	0.01	0.28	0.02
2453306.61	14.53	0.00	0.67	0.01	0.34	0.02
2453307.67	16.31	0.02	0.56	0.03	0.26	0.04
2453309.55	16.73	0.01	0.55	0.02	0.28	0.03
2453312.55	17.19	0.01	0.54	0.01	0.04	0.03
2453313.59	17.35	0.01	0.58	0.02	0.16	0.04
2453315.57	17.34	0.01	0.49	0.02	0.13	0.03
2453317.60	17.29	0.01	0.54	0.02	0.29	0.02
2453318.46	17.16	0.01	0.53	0.02	0.17	0.03
2453318.53	17.20	0.01	0.61	0.02	0.25	0.02
2453318.60	17.20	0.01	0.60	0.01	0.24	0.01
2453322.51	17.26	0.01	0.40	0.01	-0.01	0.03
2453322.54	17.33	0.01	0.54	0.02	0.07	0.03
2453384.42	13.56	0.02	0.67	0.02	0.28	0.01
2453386.36	13.49	0.02	0.68	0.02	0.25	0.03
2453388.41	13.45	0.01	0.67	0.02	0.28	0.02
2453398.21	13.46	0.04	0.67	0.04	0.26	0.02
2453400.22	13.53	0.01	0.67	0.02	0.27	0.02
2453401.22	13.61	0.01	0.69	0.02	0.28	0.02
2453405.25	16.63	0.02	0.61	0.03	0.06	0.04
2453405.28	16.64	0.02	0.54	0.03	0.25	0.03
2453405.35	16.63	0.02	0.56	0.03	0.18	0.03
2453406.28	16.81	0.01	0.54	0.02	0.28	0.03
2453406.36	16.83	0.01	0.54	0.02	0.16	0.02
2453407.21	16.95	0.01	0.55	0.02	0.22	0.02

Table 1—Continued

JD(day)	J	J err	J-H	J-H err	H-Ks	H-Ks err
2453409.37	17.22	0.02	0.45	0.03	0.24	0.02
2453411.22	17.38	0.02	0.49	0.02	-0.06	0.02
2453415.26	17.25	0.02	0.54	0.03	0.31	0.03
2453417.24	17.25	0.01	0.53	0.02	0.35	0.02
2453421.26	17.48	0.02	0.55	0.04	0.05	0.03
2453424.22	17.06	0.02	0.52	0.02	0.42	0.03
2453426.27	16.70	0.01	0.55	0.01	0.19	0.03
2453427.19	16.54	0.02	0.60	0.03	0.27	0.04
2453427.32	16.52	0.02	0.62	0.03	0.30	0.04
2453428.15	16.36	0.02	0.62	0.04	0.33	0.04
2453428.31	16.33	0.02	0.59	0.03	0.32	0.04
2453429.26	14.91	0.01	0.68	0.03	0.37	0.03
2453429.34	14.79	0.01	0.68	0.02	0.35	0.02
2453430.23	13.97	0.01	0.67	0.02	0.30	0.02
2453430.30	13.93	0.01	0.69	0.03	0.30	0.03
2453431.21	13.62	0.02	0.69	0.03	0.30	0.03
2453431.30	13.60	0.02	0.68	0.03	0.31	0.03
2453432.22	13.54	0.01	0.69	0.03	0.30	0.03
2453432.30	13.54	0.01	0.69	0.02	0.30	0.02
2453433.23	13.53	0.01	0.69	0.03	0.31	0.03
2453433.31	13.53	0.01	0.70	0.02	0.29	0.03

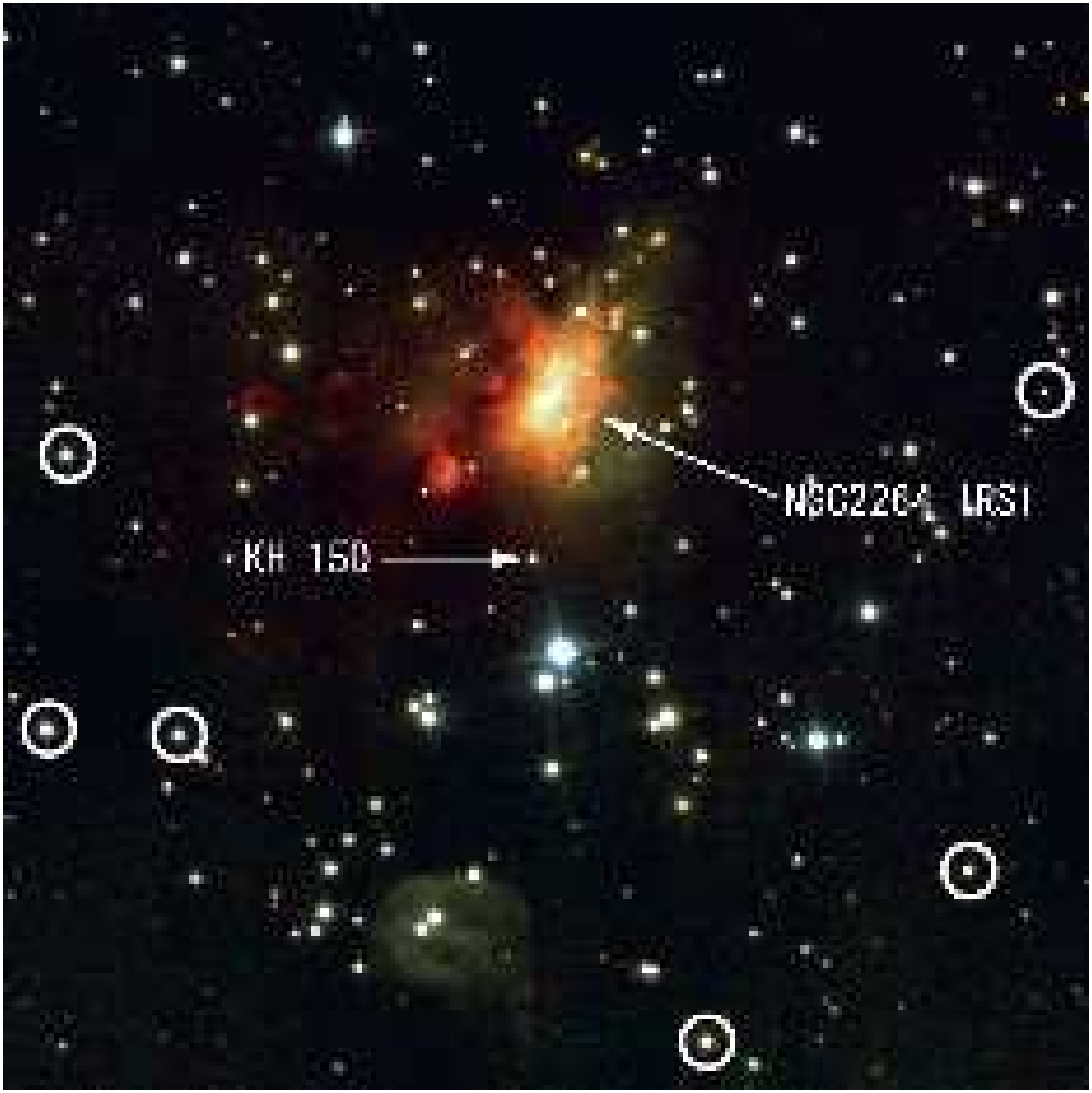

Fig. 1.— *JHKs* composite color image of the KH 15D region including NGC 2264 IRS1 and the top of the Cone Nebula (seen as a faint nebula to the south). The field of view is $7' \times 7'$. North is top and east is to the left. The six stars in circles are the reference stars used for the relative photometry. The image was obtained on 2004 October 23 when the system is out of eclipse. **Note that the image quality is significantly degraded in this preprint because of the limited file size.**

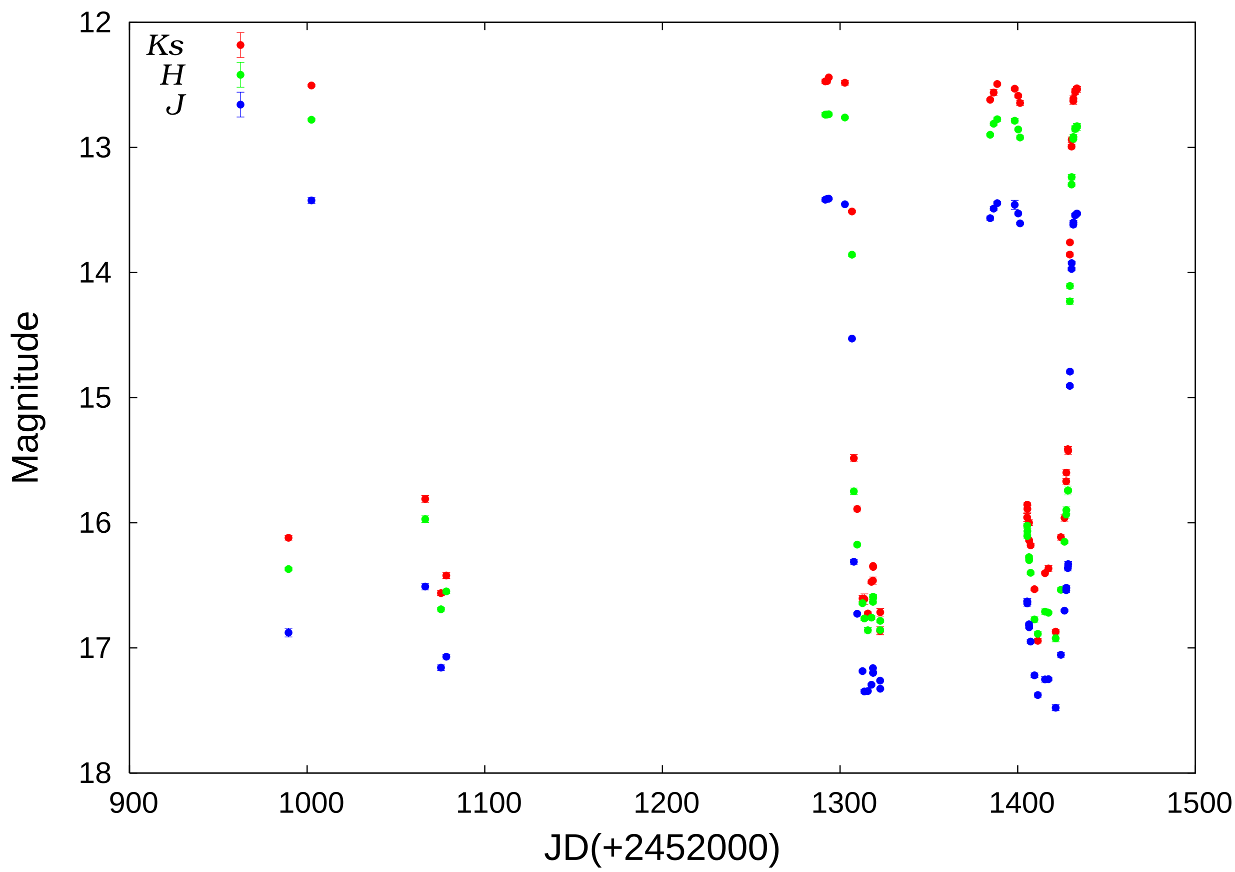

Fig. 2.— Raw (non-phased) light curves of KH 15D (*JHKs*) from 2003 December to 2005 March.

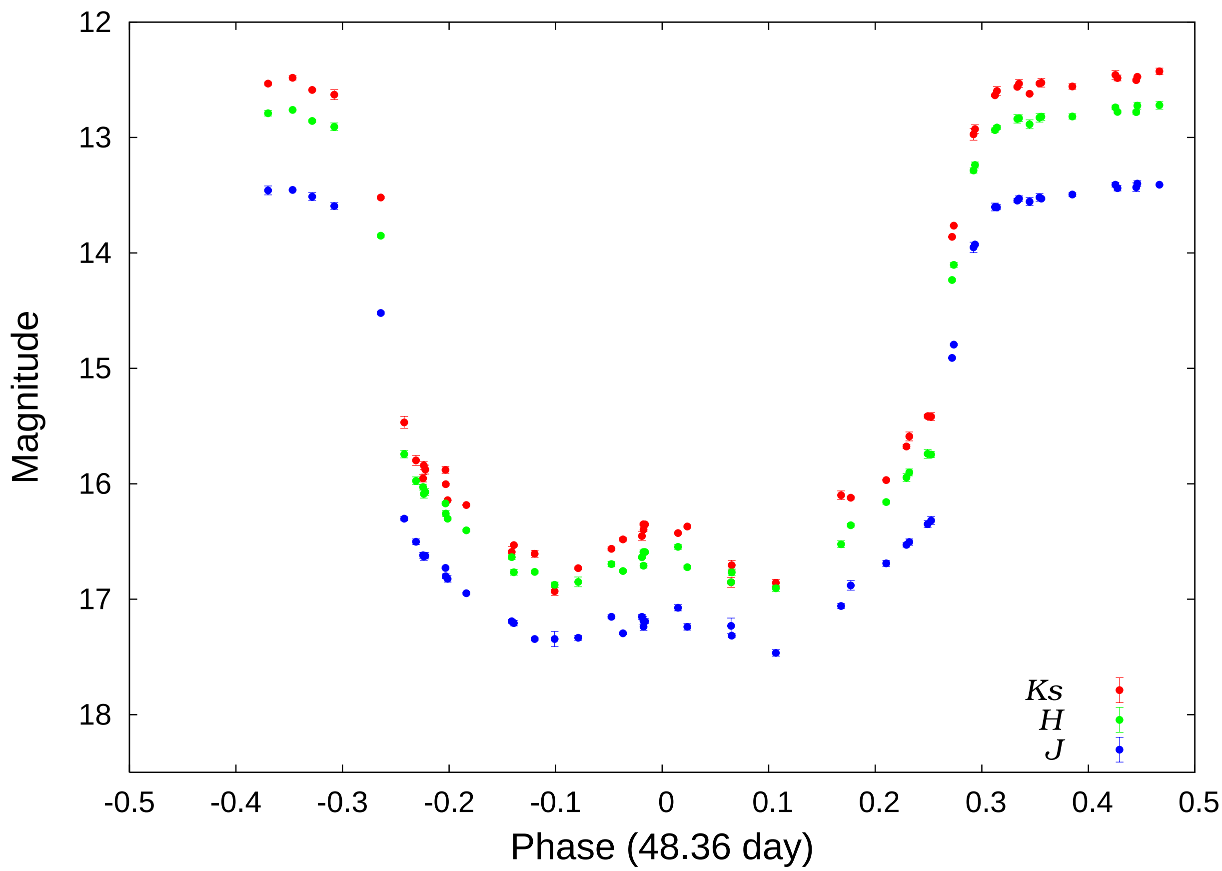

Fig. 3.— Phased light curves of KH 15D (*JHKs*) from 2003 December to 2005 March. The period of 48.36 days is used for phasing.

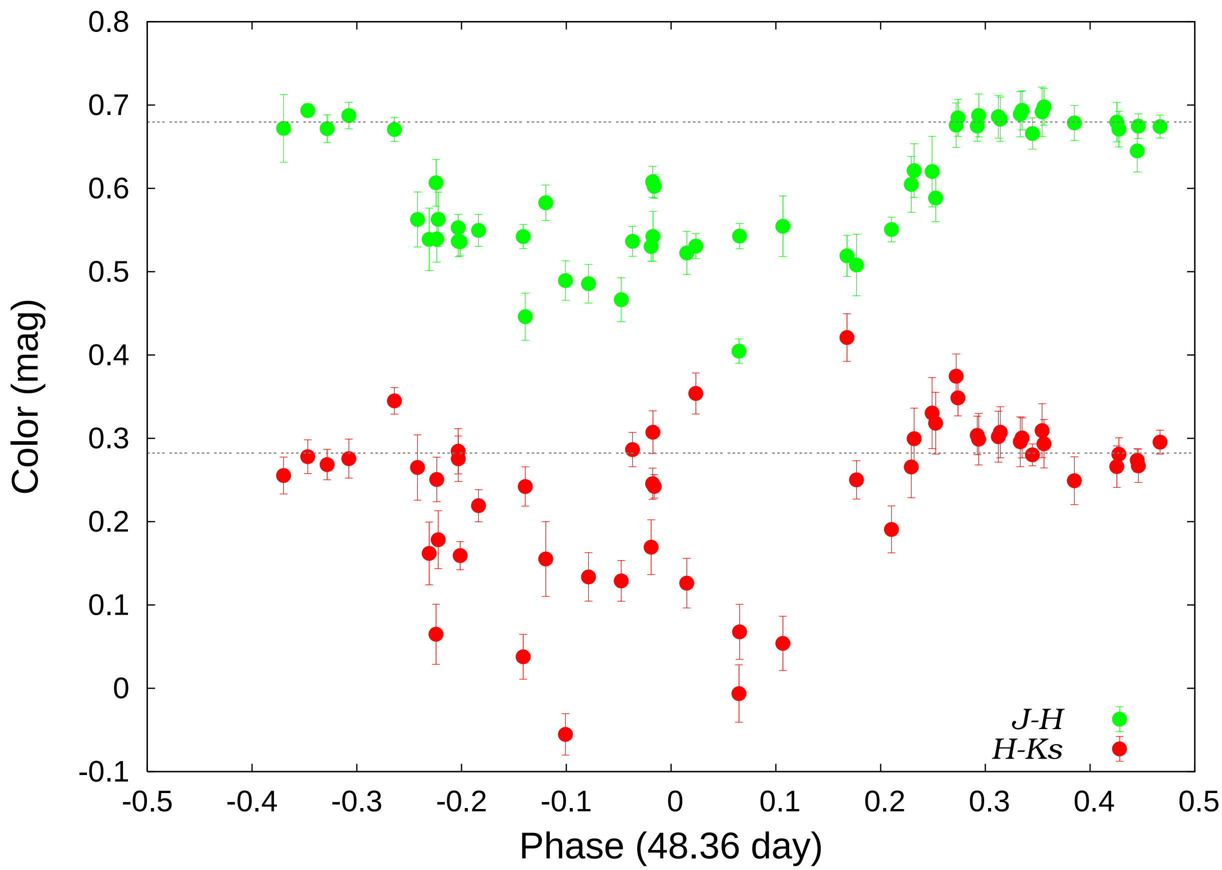

Fig. 4.— Phased color curves of KH 15D (*J*-*H*, *H*-*Ks*) from 2003 December to 2005 March. The period of 48.36 days is used for phasing. The dotted lines show the average colors outside of the eclipse.